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13. ABSTRACT *(Maximum 200 words)*

We have used our THz impulse range to measure the late time response of targets following excitation by a short THz impulse: (1) Our measurements on dielectric cylinders showed unprecedented agreement with theory in both the time and frequency domains and enabled the first direct experimental comparison for the predicted surface wave with exact numerical calculations as well a simple geometrical optics model. (2) Our measurements on dielectric spheres had sufficiently high temporal resolution to permit the surface wave contribution to the total impulse response to be isolated. These results enabled the first direct experimental comparison for the predicted surface wave with numerical calculations using the Mie theory as well as the surface wave approximation of van de Hulst. (3) We have performed a direct observation of the Gouy effect through THz impulse scattering from cylindrical and spherical targets; the Gouy phase shift through a one-axis (cylindrical) focus of $\pi/2$ in comparison with a two-axis (spherical) focus of π is required to interpret our results. (4) Using similar THz optoelectronic techniques, we have characterized the response from an impulsively-excited, micron-sized dipole antenna on a dielectric surface. These THz experimental results scale and compare well with a previous GHz geo-radar theoretical calculation of a horizontal dipole on a dielectric. (5) For the first time we have used quasi-optical methods to efficiently couple freely propagating, subpsec pulses of THz radiation into sub-mm circular metal tubes (waveguides), single crystal fibers and plastic ribbon waveguides and to consequently measure the transmitted pulses from these waveguides.

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Final Report

Optoelectronic THz Impulse Ranging

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Statement of Problem

We have developed and demonstrated some of the fastest optoelectronic circuitry in the world. Driven by ultrafast repetitive laser pulses, this circuitry allows for real time characterization on the psec and fsec time scale of a variety of high performance devices and for high bandwidth transmission line studies. Via this circuitry we have developed a complete optoelectronic THz beam system which can generate and detect 200 fsec pulses of freely propagating THz radiation with a resolution of 65 fsec and a signal-to-noise ratio of more than 3000. This performance cannot be matched by any other system. At present, this system is being copied and implemented world-wide.

An important and unique application of the THz system rests on the fact that the system can perform high resolution impulse ranging studies in the absence of an absorptive chamber. This situation results from the time gating of the receiver and the consequent ability to separate in time the desired signal from spurious reflections. This feature, together with the short wavelengths involved, makes possible realistic laboratory characterizations of radar signatures; i.e., realistic ratios of wavelength/target size are possible in addition to more realistic distance scales measured in wavelengths. These investigations are facilitated by our highest demonstrated amplitude signal to noise ratio of 10,000, corresponding to a dynamic range of 100 million for the power observable by the receiver. Within this contract interval we initiated and completed the first stage of an aggressive experimental and theoretical program with the goal of complete target identification by the delayed response from THz impulse excitation.

I. Introduction

A potentially simple way to identify complex targets is by the late time response after illumination by a short pulse. For this case a short pulse excites resonances within and between scattering centers on the target which are aspect independent. After detection of the initial reflected pulse, or specular reflection, the excited resonant modes radiate the late time response. Recent work has examined the late time response for target identification, in both the time and frequency domain. Besides providing a potentially simple way to identify target characteristics, measurement of the response of an object to a short excitation pulse may also provide information on the physical processes responsible for the scattered field, which is often unavailable or obscured in frequency domain measurements. To develop time domain target identification methods it is important to correlate theoretical predictions with data from actual scattering experiments. Since it is often impractical to obtain ranging data on full scale targets, geometrically scaled targets are often used in conjunction with theoretical models and measurements from actual targets.

Here we describe our results, achieved during this contract interval, involving the use of optoelectronic techniques to generate single cycle pulses of freely propagating THz radiation, and thereby demonstrating ultrawide bandwidth scattering from both metal and dielectric simple

geometrical targets. These pulses are the best approximation to impulse excitation ever used in ranging studies and have an absolute bandwidth larger than any other previously reported. The relatively short wavelengths of the THz pulse permit target features of less than 1 mm to be observed, making this technique ideal for scale ranging measurements since realistic target to wavelength ratios can be maintained. Furthermore, the measurement window achieved by the optoelectronic gating technique together with the subpsec response time of the detector enables only the scattered signal from the target to be detected, providing background free measurements.

II. Experiment

The experimental system has been has been described in detail in previous progress reports and in the publications generated under this contract.[1,2,7]

III. Theory

The theoretical approach has been has been described in detail in previous progress reports and in the publications generated under this contract.[1,2,7]

Program Results with Optoelectronic THz Impulse Ranging

Late Time Target Response Measured with THz Impulse Ranging[1,7]

Within this contract interval time domain impulse scattering of freely propagating single cycle THz radiation from dielectric targets has been measured in the far field with sub-picosecond resolution. The initial specular reflection as well as the late time response of the targets was observed to approximately 100 times the initial pulse width. The measured scattered fields agree well with the calculated scattering for early and late time response in both the time and frequency domains. The data was fit to both an exact result from an inverse Fourier transform of calculated frequency domain scattering as well as an intuitive model based on physical optics. The physical optics picture was verified directly in the time domain, and surface wave propagation velocities were measured.

Temporal Isolation of the Scattering Mechanisms from Dielectric Spheres Responsible for the Terahertz Glory[2]

The surface wave scattering processes responsible in part for the optical glory have never been compared with theoretical predictions. We have used THz impulse ranging to measure the time domain impulse response of spherical targets with sufficiently high temporal resolution to permit the surface wave contribution to the total impulse response to be isolated. Consequently, the first direct experimental comparison for the surface wave with numerical calculations using the Mie theory as well as the surface wave approximation of van de Hulst and a simple geometrical optics model was performed. Comparing the measured time dependent scattered pulse structure with the geometrical model allows a direct measurement of the velocity of surface wave propagation. Through a numerical Fourier transform of the scattered surface waveform the amplitude and phase of the Fourier components were determined and the complex propagation coefficients of the surface wave were directly measured. Interference of the surface waves from a dielectric sphere were shown to lead to the frequency and angular intensity dependence of the THz glory.

Direct Observation of the Gouy Phase Shift[10]

Within the contract interval we have performed a unique and direct observation of the Gouy effect through THz impulse scattering from cylindrical and spherical targets. As obtained here for the first time, an understanding of the Gouy phase shift through a one-axis (cylindrical) focus of $\pi/2$ in comparison with a two-axis (spherical) focus of π is required to interpret our scattering results using a time domain physical optics (PO) model for scattering.

Variable Angle Bistatic THz Impulse Ranging[15]

We have demonstrated for the first time variable angle THz impulse ranging. This has permitted the direct measurement of the surface wave loss and dispersion at terahertz frequencies. Future applications of this capability include novel imaging and nondestructive evaluation.

Experimental Time-Domain Study of THz Signals from Impulse Excitation of a Surface Dipole (On-Chip Impulse Ranging)[6]

Using optoelectronic techniques with subps resolution, we have characterized the electric field time-domain response from an impulsively-excited, micron-sized dipole antenna on a dielectric surface. When detected by an adjacent dipole antenna 400 microns distant, two primary signals were observed, a far field pulse reflected from the back surface of the substrate and a near field surface pulse. Consistent with the existing theoretical understanding, no far field radiation propagation was detected along the surface; in contrast the near field emission appeared as two distinct surface-propagating pulses despite originating from the dipole simultaneously.

The observed freely propagating, far field THz signal with its clean bipolar characteristic and subps pulse width is well suited for high frequency on chip communication or synchronous triggering of electrically isolated circuits as well as interchip communication. The second signal pulse, which was due to the near field component, consisted of two distinct pulses. These two near field pulses have the same pulse shape, the time integral of the far field radiation pulse; one pulse is inverted with respect to the other. It was observed that the THz experimental results scale and compare well with a GHz geo-radar theoretical calculation of a horizontal dipole on a dielectric, excited by an electrical impulse 1000 times longer than that used in this experiment. This correspondence suggests that macroscopic geological problems could be studied by our techniques, if modeled appropriately on the laboratory scale. It is also concluded that the range and characteristics of the near field pulse are important issues which need to be considered when designing any ultrashort electrical pulse systems as well as in the design of ultrafast on chip communication architectures. The experimental study also demonstrates the potential use of the far field pulse for on chip communication of picosecond pulses of THz radiation.

Propagation of Ultra-Wideband, Short Pulses of THz Radiation through Sub-mm Diameter Circular Metal Waveguides (A New THz Technology)[9]

Within the contract interval we have used quasi-optical methods to efficiently couple freely propagating, subpsec pulses of THz radiation into sub-mm circular metal tubes (waveguides) and to consequently, measure the transmitted pulses from these waveguides. This new THz capability couples together waveguide and freely propagating wave technology. The potential impact on our ranging studies is being assessed. We observe very dispersive, low-loss waveguide propagation over the frequency band from 0.65 to 3.5 THz, with frequency dependent group velocities v_g ranging from c/4 to c and phase velocities v_p from 4c to c, where ($v_g v_p = c^2$). Even though our input spectrum overlaps the cut-off frequencies of more than 25

waveguide modes, the linearly polarized incoming THz pulses only significantly couple into the TE_{11}, TM_{11} and the TE_{12} modes. Our observations are in agreement with waveguide theory and were obtained using 24 mm long and 4 mm long stainless steel tubes with inside diameters of 240 μm and 280 μm, respectively.

Single-mode Waveguide Propagation and Reshaping of Sub-ps Terahertz Pulses in Sapphire Fibers (A New THz Technology)[12]

An alternative approach to metal waveguides would be to use dielectric waveguides. Such waveguides would not have the sharp low-frequency cut-off of metal waveguides and would thereby extend the low frequency limit. Given a suitable low loss dielectric, such as high-resistivity silicon with a power absorption coefficient of less than $0.05\,\mathrm{cm}^{-1}$ over our frequency range, dielectric waveguides could have much less absorption than metal waveguides. In addition, due to boundary considerations it should be possible to more cleanly couple, and with a much higher coupling efficiency, linearly polarized THz radiation into the single dominant mode for dielectric waveguides than for metal circular waveguides. Such dielectric single-mode THz waveguides would have the promise of an extremely low-loss, flexible interconnect and communications channel, with advantages similar to that of single-mode optical fiber.

Within this contract interval we have demonstrated the single-mode propagation of sub-ps THz pulses in dielectric waveguides (fibers). These demonstrations prove the efficient quasi-optical input and output coupling to and from such fibers and show the viability of the single-mode THz fiber interconnect. The fact that the diameters (325 μm, 250 μm and 150 μm) of the THz fibers are similar to those of optical fibers, including the core and cladding, gives the THz fibers similar flexibility and handling properties. Because this work was performed with single-crystal unclad fibers, the waveguide propagation characteristics vary significantly over the extensive frequency spectrum of the nearly single-cycle input pulses, giving rise to considerable absorptive and dispersive reshaping. Good agreement between theory and experiment is obtained by analyzing the propagation in terms of the single HE_{11} waveguide mode. The dominance of the single HE_{11} mode, despite the fiber dimensions allowing for multimode propagation, is attributed to the free-space to waveguide coupling.

Plastic Ribbon THz Waveguides (A New THz Technology)[13]

By configuring the dielectric waveguide into the form of a thin, wide ribbon, it is possible to reduce the attenuation constant considerably below that of the bulk material of the ribbon, due to the small filling factor caused by the extensive fringing fields. The ribbon waveguide structure can be made with flexible, low-loss dielectric materials. Equivalent or even better quasi-optic coupling than for the circular case is expected. The structure is amenable to photolithographic techniques due to the planar geometry, thereby allowing active and passive devices to be integrated with the waveguide.

Within this contract interval, we performed an experimental study and obtained a theoretical explanation of single-mode propagation and quasi-optic coupling of picosecond THz pulses in plastic ribbon waveguides. The feasibility of this type of waveguide as a transmission line and a circuit interconnect for the THz frequency region was thereby demonstrated. Dispersive, low-loss propagation was observed within the bandwidth from 0.1 to 3.5 THz for 2 cm wide ribbon waveguides made of high-density polyethylene (HDPE), having nominal dimensions of 150 μm (thick) by 10.0 mm (long), and 120 μm (thick) by 20.0 mm (long). The large group velocity dispersion (GVD) of the waveguide causes extensive pulse reshaping and broadening, resulting in positively chirped output pulses. The experiment and calculations based on the well-known 2-D waveguide model showed that the linearly polarized (perpendicular to the plane of the ribbon) incoming THz beam couples predominantly to the

dominant TM_0 mode resulting in single-mode propagation, even though the wideband input spectrum extends beyond the cutoff frequencies of several higher-order modes.

List of Publications: (Citations in the above report use these same numbers)

1. R.A. Cheville, R.W. McGowan and D. Grischkowsky, "Late Time Target Response Measured with THz Impulse Ranging," IEEE Transactions on Antennas and Propagation, Vol. 45, pp. 1518-1524 (1997).
2. R.A. Cheville, R.W. McGowan and D. Grischkowsky, "Temporal Isolation of the Scattering Mechanisms from Dielectric Spheres Responsible for the Terahertz Glory," Phys. Rev. Lett., Vol. 80, 269-272 (1998).
3. R.W. McGowan, D. Grischkowsky and J.A. Misewich, "Demonstrated Low Radiative Loss of a Quadrupole Ultrashort Electrical Pulse Propagated on a Three Line Coplanar Transmission Line," Appl. Phys. Lett., Vol. 71, pp. 2842-2844 (1997).
4. Tae-In Jeon and D. Grischkowsky, "Observation of a Cole-Davidson Type Complex Conductivity in the Limit of Very Low Carrier Densities in Doped Silicon," Appl. Phys. Lett., Vol. 72, pp. 2259-2261 (1998).
5. Tae-In Jeon and D. Grischkowsky, "Characterization of Optically-Dense, Doped Semiconductors by Reflection THz Time-Domain Spectroscopy," Appl. Phys. Lett., Vol. 72, pp. 3032-3034 (1998).
6. R.W. McGowan and D. Grischkowsky, "Experimental Time-Domain Study of THz Signals from Impulse Excitation of a Surface Dipole," Appl. Phys. Lett., Vol. 74, pp. 1764-1766 (1999).
7. R.W. McGowan, R.A. Cheville and D. Grischkowsky, "Experimental Study of the Surface Waves on a Dielectric Cylinder via THz Impulse Radar Ranging," IEEE Trans. On Microwave Theory and Techniques, Vol. 48, pp. 417-422 (2000).
8. G. Gallot, Jiangquan Zhang, R.W. McGowan, Tae-In Jeon and D. Grischkowsky, "Measurements of the THz Absorption and Dispersion of ZnTe and their Relevance to the Electro-Optic Detection of THz Radiation," Appl. Phys. Lett., Vol. 74, pp. 3450-3452 (1999).
9. R.W. McGowan, G. Gallot, and D. Grischkowsky, "Propagation of Ultra-Wideband, Short Pulses of THz Radiation through Sub-mm Diameter Circular Waveguides," Optics Letters, Vol. 24, pp. 1431-1433 (1999).
10. R.W. McGowan, R.A. Cheville, and D. Grischkowsky, "Direct Observation of the Gouy Phase Shift in THz impulse Ranging," Appl. Phys. Lett., Vol. 76, pp. 670-672 (2000).
11. G. Gallot, S. Jamison, R.W. McGowan and D. Grischkowsky, "THz Waveguides," J. Opt. Soc. Am. B., Vol. 17, pp. 851-863 (2000).
12. S.P. Jamison, R.W. McGowan and D. Grischkowsky, "Single-mode Waveguide Propagation and Reshaping of Sub-ps Terahertz Pulses in Sapphire Fibers," Appl. Phys. Lett., Vol. 76, pp. 1987-1989 (2000).
13. R. Mendis and D. Grischkowsky, "Plastic ribbon THz waveguides," J. Appl. Phys. Vol. 88, pp. 4449-4451 (2000).
14. Tae-In Jeon, D. Grischkowsky, A.K. Mukherjee and Reghu Menon, "Electrical Characterization of Conducting Polypyrrole by THz Time-Domain Spectroscopy," to be published in Appl. Phys. Lett., October 16, 2000.
15. M.T. Reiten, D. Grischkowsky, and R.A. Cheville, "Isolation of surface waves through bistatic terahertz impulse ranging," submitted to Appl. Phys. Lett., April 14, 2000.

Invited Conference Presentations

C1. R.A. Cheville, R. McGowan and D. Grischkowsky, "Impulse Ranging with THz Pulses," Annual Meeting of the Optical Society of America, Rochester, New York, October 20-24, 1996.

C2. D. Grischkowsky and R.A. Cheville, "Scale Ranging with subpsec Pulses of THz Radiation," IEEE Lasers and Electro-Optics Society 1996 Annual Meeting, Boston, Massachusetts, November 18-21, 1996. (Proceedings Published).

C3. R.A. Cheville, R.W. McGowan and D. Grischkowsky, "THz Impulse Ranging," Ultrafast Electronics and Optoelectronics Topical Meeting, Incline Village, Nevada, March 17-19, 1997 (Proceedings Published).

C4. D. Grischkowsky and R. A. Cheville, "Unique Applications of THz Spectroscopy," ILS-XIII, 13th Interdisciplinary Laser Science Conference, Long Beach, California, October 12-17, 1997. (The ranging studies were included in this broad title)

C5. R.A. Cheville, R.W. McGowan and D. Grischkowsky, "Present Applications and Future Possibilities of THz Time-Domain Spectroscopy (THz-TDS)," Lasers 98 Conference, December 7-11, 1998, Tucson, Arizona. (The ranging studies were included in this talk)

C6. D. Grischkowsky, "Unique Applications enabled by Optoelectronic THz Techniques, THz Time-Domain Spectroscopy (THz-TDS) and THz Impulse Ranging," Nonlinear Optics and Lasers Gordon Conference, July 25-30, 1999, New London, New Hampshire.

C7. R.A. Cheville, M.T. Reiten, R.W. McGowan and D. Grischkowsky, "New Directions in THz Ranging," Conference on Lasers and Electro-Optics and Quantum Electronics and Laser Science Conference, May 7-12, 2000, San Francisco, California. (Technical Digest Published).

C8. D. Grischkowsky, "Generation and Applications of Ultrafast THz Pulses," Canadian Association of Physicists' 2000 Congress, June 4-7, 2000, Toronto, Canada.

C9. D. Grischkowsky, "Ultrafast Applications of THz Waveguides," 12th International Conference on Ultrafast Phenomena, July 9-13, 2000, Charleston, South Carolina. (Proceedings Published).

Project Participants

Senior Personnel

Daniel R. Grischkowsky, (Bellmon Professor of Optoelectronics, **Project PI**), Responsible for strategy, leadership and execution of experiments and theory. Determines areas of investigation. Together with his research team designs experiments and interprets results and compares with theory.

Richard A. Cheville, (initially appointed as Res. Associate, later promoted to Visiting Asst. Prof., then hired as tenure track Asst. Prof.), Designs and carries out laboratory experiments and develops theoretical models to explain the observations in collaboration with the PI, Post-Docs, graduate and undergraduate students.

Post-Doctoral Fellows, Visiting Profs. and Research Scientists

Steven Jamison, (Post-Doctoral Fellow), Carries out laboratory experiments and performs numerical calculations to explain the observations in collaboration with the PI, Post-Docs,

graduate and undergraduate students, main theme of his work has been guided wave propagation of THz pulses involving metal and dielectric waveguides.

Tae-In Jeon, (started as Graduate Student-Res. Asst., graduated May 1997, then promoted to Post. Doctoral Fellow, then went back to Korea as a tenure track Asst. Prof., comes back to OSU to perform research as Visiting Asst. Prof.), Research training and work involved THz-TDS measurements of semiconductors and development of surface THz-TDS.

Roger McGowan, (initially appointed as a Post-Doctoral Fellow, was later promoted to Visiting Asst. Prof, has now relocated from OSU to Imation, Inc.), Carries out laboratory experiments and performs numerical calculations to explain the observations in collaboration with the PI, Post-Docs, graduate and undergraduate students, main themes of his work have been THz ranging and guided wave propagation of THz pulses.

Marcus Wolff, (initial 6 month appointment was as a Post. Doctoral Fellow, later came back as a Visiting Asst. Prof.), Carries out laboratory experiments and performs numerical calculations to explain the observations in collaboration with the PI, Post-Docs, graduate and undergraduate students), latest responsibilities include developing the lithographic process for our optoelectronic chips in the newly commissioned OSU-ATRC cleanroom.

Weili Zhang, (Visiting Assoc. Prof.), Carries out laboratory experiments and performs numerical calculations to explain the observations in collaboration with the PI, Post-Docs, graduate and undergraduate students, main themes of his work have been using THz ranging techniques to couple to a dielectric high-Q resonator.

Graduate Students

William M. Baker, (Graduate Student-Res. Asst.), Research training and work involved development and testing of a THz interferometer and the investigation of methods to increase the power of the THz transmitter by an order of magnitude, withdrew from Ph.D. program to join private industry.

Rajind Mendis, (Graduate Student-Res. Asst.), Research training and work has involved the investigation of the comparative advantages of electro-optic detection of THz radiation as compared to dipole antennas, compared THz-TDS with Fourier transform spectroscopy, and the study of photonic bandgap materials, and most recently has concentrated on the development and understanding of THz planar waveguides.

John O'Hara, (Graduate Student-Res. Asst.), Research training and work has involved setting up and experiment to demonstrate the efficacy of THz quasi-coptical imaging techniques. He has developed a complete theoretical understanding of his observations.

Vasavi Vemuri, (was Graduate Student-Res. Asst., Received M.S. in Elect. Engr., Aug. 1999, is now employed in private industry), Research training and work involved the set up and demonstration of a small focus THz-TDS spectrometer. Previously impossible measurements have been made with this system.

Jiangquan Zhang, (Graduate Student-Res. Asst.), Research training and work has involved commissioning a new THz-TDS set-up in our additional laboratory space and THz-TDS measurements of electro-optic materials and conducting polymers.

Undergraduate Students

Johnathon Allen, (Undergraduate student), Research training through laboratory support and a selection of smaller focused projects.

Jeffery S. Daniels, (was Undergraduate student, Graduated in May, 2000 with a B.S. in Elect. Engineering, and is now employed in private industry), Research training through laboratory support and a selection of smaller focused projects.

Bradlee Harmon, (Undergraduate student), Research training through laboratory support and a selection of smaller focused projects.

John Madison, (Undergraduate student), Research training through laboratory support and a selection of smaller focused projects.

Report of Inventions: None

Technology Transfer:
D. Grischkowsky, and R.A. Cheville, "THz Time Domain Spectrometer", Sub-Contract awarded (July 1, 1998) to Clark-MXR, Inc. for $195,000 as part of a Phase II, SBIR Proposal to NSF.